Progress Report to AOARD

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14. ABSTRACT
In the past few years, we have been performing the research on the growth and characterization of InGaN/GaN nanostructures. Based on those nanostructures, we fabricated efficient dual-color and white-light light-emitting diodes. Meanwhile, we studied the coupling between surface plasmon and InGaN/GaN quantum wells for enhancing the emission efficiency. The detailed research topics are shown as follows 1. Prestrain growth of InGaN/GaN quantum wells for increasing indium incorporation 2. Fs pump-probe study on ultrafast carrier dynamics in InGaN of nanostructures 3. Simulation study on carrier capture by Nano-clusters in InGaN 4. Surface plasmon coupling with InGaN/GaN quantum wells for light emission manipulation 5. Fabrications of blue/green dual-color and white light-emitting diodes 6. Optical and material characterization of ZnO nanostructures 7. Fabrication of anodized-aluminum-oxide (AAO) ? preparing for patterned InGaN/GaN nano-column growth Also, in cooperating with the scientists at AFRL, we performed the following studies a. Characterization of GaN nano-columns b. GaN over-growth on GaN nano-columns

15. SUBJECT TERMS
Electronics , Optoelectronic Materials, Semiconductor Materials, Solar Cells

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Topics under Study

Theme: MOCVD and MBE growths of nitride and oxide semiconductor nanostructures for energy technology applications

Research Topics:

1. All-semiconductor White-light LED --- Stacking multi-parameter InGaN/GaN QWs with MOCVD for white-light LED fabrication
2. Dislocation-free Nitride --- Patterned growth and coalescence over-growth of InGaN nano-columns with MOCVD (cooperating with AFRL)
3. Nano-photonics --- Surface plasmon coupling with InGaN/GaN quantum wells for enhancing light emission
4. Growth of ZnO-related compounds --- ZnO/GaN hybrid growth with MBE for efficient LED fabrication
5. Nitride-based Solar Cell --- Using InGaN for improving the efficiency of solar cell

1. All-semiconductor White-light LED (1)

Stacking multi-parameter InGaN/GaN QWs with MOCVD for white-light LED fabrication

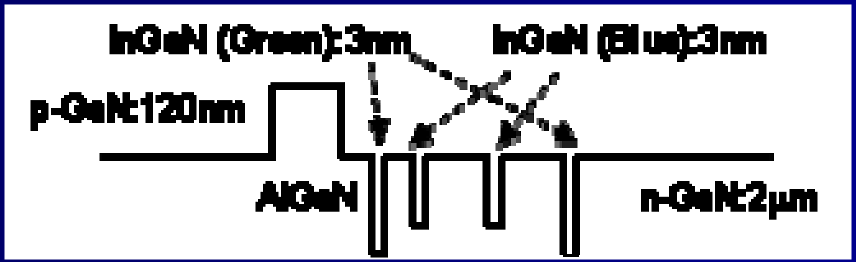
Problem: Currently, all solid-state white-light sources use phosphors to convert photon colors.

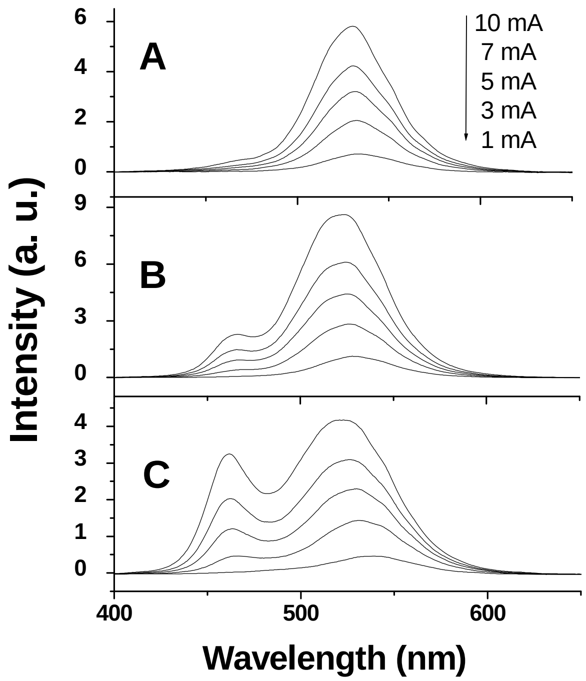
Difficulties in using phosphors:

1. Sensitive color shifting from the variation of phosphor thickness and pumping wavelengths
2. Patents are controlled.
3. Energy conversion is inefficient.

Approach: Use InGaN/GaN QWs of different indium contents for emitting blue, green and red lights.

We have fabricated color contrast controllable blue/green 2-color LED by stacking two different QWs.





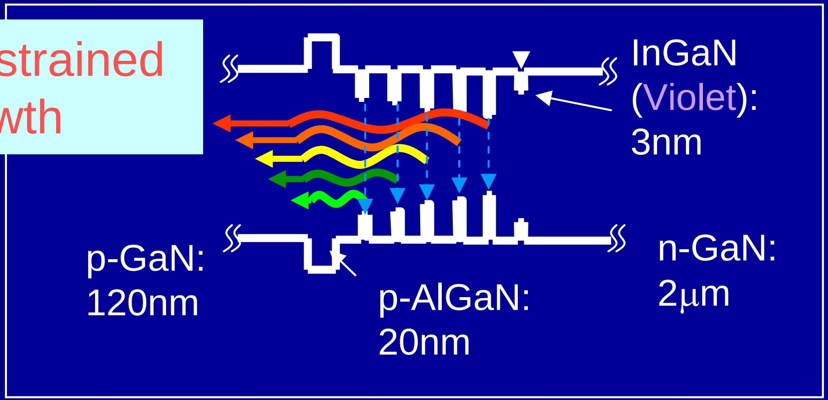
H. S. Chen et al., Appl. Phys. Lett. **89**, 093501 (2006).

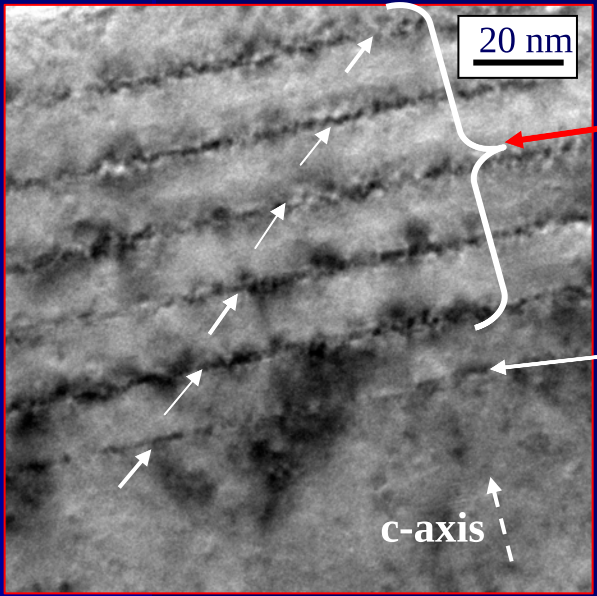
1. All-semiconductor White-light LED (2)

Prestrained growth for increasing indium incorporation for red-LED fabrication

Uniqueness: Although some related sporadic reports were found in literature, our systematic study on all-semiconductor white-light LED with novel ideas is unique in the world.

Huang et al., Appl. Phys. Lett. **89**, 051913 (2006).

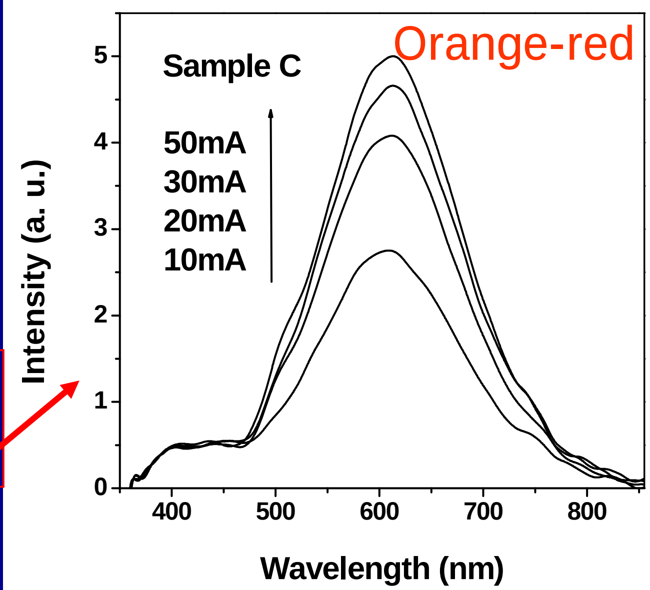




TEM image of five prestrained InGaN/GaN QWs

QW to produce prestrain

Fabrication of orange-red LED

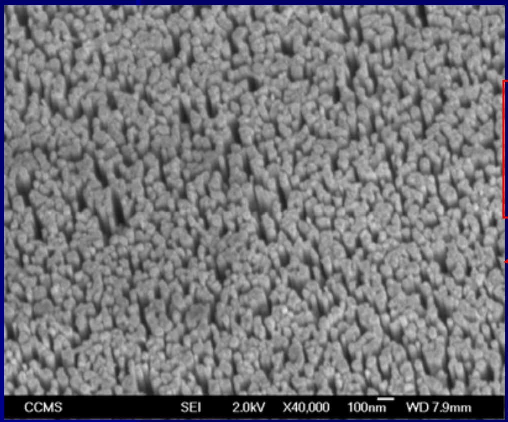


H. S. Chen et al, IEEE Photon. Technol. Lett. **18**, 2269 (2006).

2. Dislocation-free Nitride

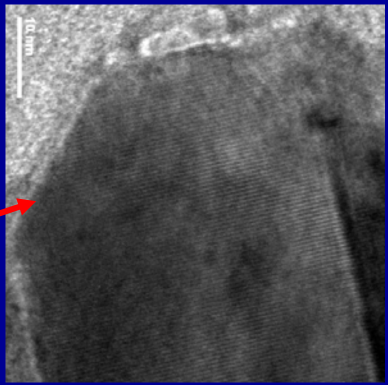
Patterned growth and coalescence over-growth of InGaN nano-columns with MOCVD (cooperating with AFRL)

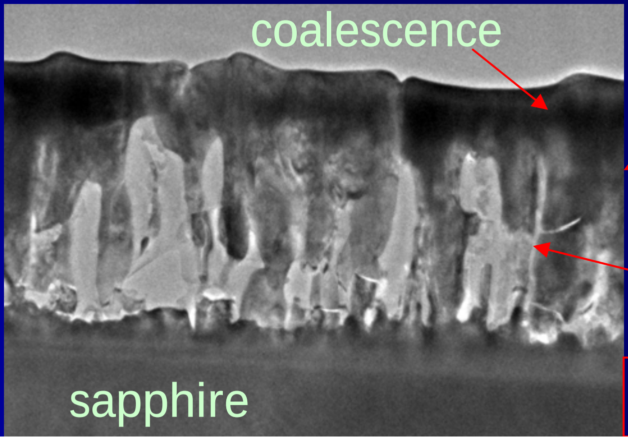
Problem: High threading dislocation density in GaN
Approach: Nano-column growth and then coalescence growth
Uniqueness: Prof. Kishino of Sophia University, Japan, also reported the coalescence growth



SEM image of GaN nano-columns on sapphire substrate

TEM image of a single nano-column – dislocation free

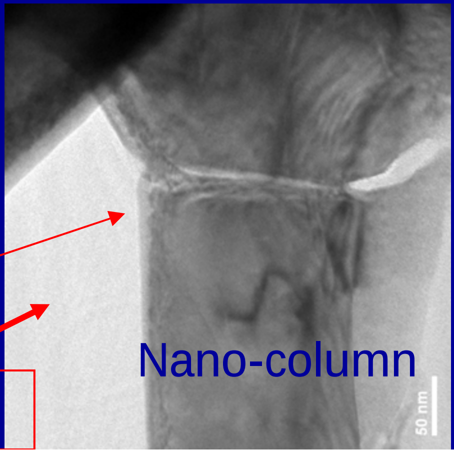




TEM image of coalescent GaN nano-columns

nano-columns

junction

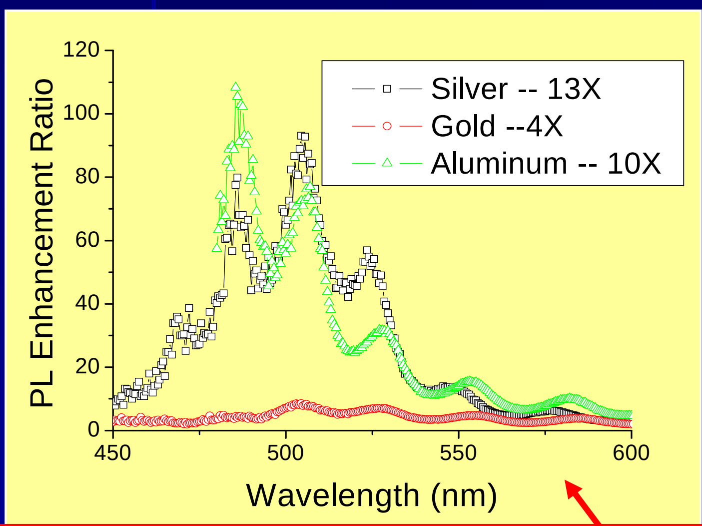


TEM image of a re-growth junction

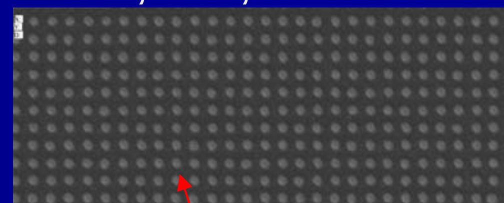
3. Nano-photonics

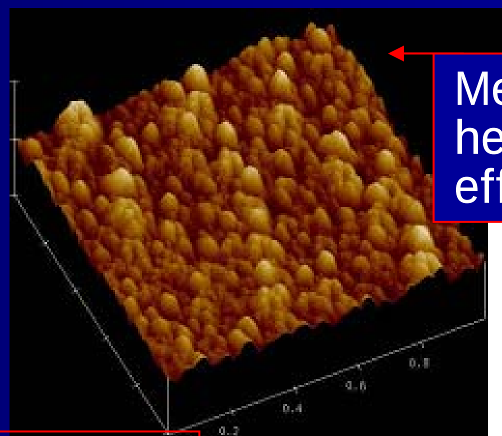
Surface plasmon coupling with InGaN/GaN quantum wells for enhancing light emission

Problem: Light emission efficiency of green-red emission is low.
Approach: Use surface plasmon coupling with QWs for enhancing efficiency
Uniqueness: competing with Dr. K. Okamoto, Caltech, CA, US

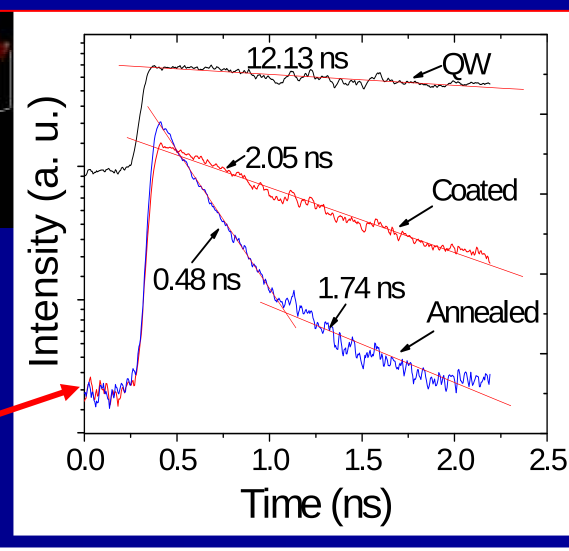


C. Y. Chen et al., Appl. Phys. Lett. **89**, 203113 (2006).





Metallic nanostructures can help in phase matching for effective emission.



Different metals have different enhancement ratios in a particular wavelength range.

The reduction of time-resolved photoluminescence decay time confirms the occurrence of surface plasmon coupling.

Three-year Plan
(January 2007 – December 2009)

1. Growth of Semiconductor Nanostructure (SNS)

-- Patterned and un-patterned MOCVD growths of InGaN/GaN nano-columns *(cooperating with AFRL)*

-- Patterned and un-patterned MOCVD growths of InGaN/GaN quantum dots

-- MOCVD growth of indium-rich InGaN quantum-well structures

-- M-plane and A-plane MOCVD InGaN/GaN growth for fabricating polarized LEDs

-- MBE growth of CdZnMgO quantum wells for high-efficiency emission

-- Hybrid growth of ZnO/GaN LED structures for high-efficiency emission

2. Surface Plasmon (SP) Coupling with Semiconductor Nanostructures

-- Dissipation and radiation rates of SP in a particular metallic structure

-- Roles of phonons of semiconductors and metals in the SP-SNS coupling process

-- SP properties in semi-metal-semi-semiconductor structures

-- Role of the quantum-confined Stark effect in a QW in SP-SNS coupling

-- Fundamental properties of InGaN/GaN photonic crystal membranes

3. Solid-state Lighting and Solar Cell Applications

-- Use of the SP-SNS coupling process for enhancing the LED emission efficiency

-- LEDs with light emission properties controlled by photonic crystal membranes

-- InGaN-based solar cell for the tandem operation and higher efficiency

-- Fabrication of polarized LEDs

Related SCI Publications (1)

January 2006 – November 2006

1. C. F. Lu, D. M. Yeh, H. S. Chen, C. F. Huang, J. J. Huang, and C. C. Yang, "Junction temperature-controlled spectrum in a two-color InGaN/GaN quantum-well light-emitting diode," accepted for publication in IEEE Photonics Technology Letters.
2. Y. S. Chen, L. J. Yao, Y. L. Lin, L. Hung, C. F. Huang, T. Y. Tang, J. J. Huang, W. Y. Shiao, and C. C. Yang, "Transmission Electron Microscopy Study on Pre-strained InGaN/GaN Quantum Wells," J. Crystal Growth **297**, 66 (2006).
3. H. S. Chen, C. F. Lu, D. M. Yeh, C. F. Huang, J. J. Huang, and C. C. Yang, "Orange-red light-emitting diodes based on a pre-strained InGaN/GaN quantum-well epitaxy structure," IEEE Photonics Technology Letters **18**, 2269 (2006).
4. C. Y. Chen, D. M. Yeh, Y. C. Lu, and C. C. Yang, "Dependence of Resonant Coupling between Surface Plasmons and an InGaN Quantum Well on Metallic Structure," Applied Physics Letters **89**, 203113 (2006).
5. H. S. Chen, D. M. Yeh, C. F. Lu, C. F. Huang, J. J. Huang, and C. C. Yang, "Mesa-size-dependent color contrast in flip-chip blue/green two-color InGaN/GaN multi-quantum-well micro-light-emitting diodes," Applied Physics Letters **89**, 093501 (2006).
6. C. F. Huang, T. Y. Tang, J. J. Huang, W. Y. Shiao, C. C. Yang, C. W. Hsu and L. C. Chen, "Prestrained effect on the emission properties of InGaN/GaN quantum-well structures", Applied Physics Letters **89**, 051913 (2006).
7. H. C. Wang, Y. C. Lu, C. Y. Chen, and C. C. Yang, "Carrier capture times of the localized states in an InGaN thin film with indium-rich nanocluster structures," Applied Physics Letters **89**, 011906 (2006).

Related SCI Publications (2)

January 2006 – November 2006

8. S. C. Chin, C. Y. Chi, Y. C. Lu, L. Hong, Y. L. Lin, F. Y. Jen, C. C. Yang, B. P. Zhang, Y. Segawa, K. J. Ma, and J. R. Yang, "Nano-structure Study of ZnO Thin Films on Sapphire Grown with Different Temperature Conditions," J. Crystal Growth **293**, 344 (2006).

9. H. S. Chen, D. M. Yeh, C. F. Lu, C. F. Huang, W. Y. Shiao, J. J. Huang, C. C. Yang, I. S. Liu and W. F. Su, "White-light generation with CdSe/ZnS nano-crystals coated on an InGaN/GaN quantum-well blue/green two-wavelength light-emitting diode", IEEE Photonics Technology Letters **18**, 1430 (2006).

10. D. M. Yeh, C. F. Huang, H. S. Chen, T. Y. Tang, C. F. Lu, Y. C. Lu, J. J. Huang, C. C. Yang, I. S. Liu and W. F. Su, **"**Control of the Color Contrast of a Polychromatic Light-emitting Device with CdSe/ZnS Nano-crystals on an InGaN/GaN Quantum-well Structure," IEEE Photonics Technology Letters **18**, 712 (2006).

11. W. Y. Shiao, C. Y. Chi, S. C. Chin, C. F. Huang, T. Y. Tang, Y. C. Lu, Y. L. Lin, L. Hong, F. Y. Jen, C. C. Yang, B. P. Zhang and Y. Segawa, "Comparison of Nanostructure Characteristics of ZnO Grown on GaN and Sapphire," J. Applied Physics **99**, 054301 (2006).

12. H. S. Chen, D. M. Yeh, Y. C. Lu, C. Y. Chen, C. F. Huang, T. Y. Tang, C. C. Yang, C. S. Wu, and C. D. Chen, "Strain Relaxation and Quantum Confinement in InGaN/GaN Nano-posts," Nanotechnology **17**, 1454 (2006).

13. C. C. Teng, H. C. Wang, T. Y. Tang, Y. C. Lu, Y. C. Cheng, C. C. Yang, K. J. Ma, W. M. Wang, C. W. Hsu, and L. C. Chen, "Depth Dependence of Optical Property beyond the Critical Thickness of an InGaN Film," J. Crystal Growth **288**, 18 (2006). **(Invited)**